

THE ELECTRA KrF LASER PROGRAM*

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Abstract

Electra is a repetitively pulsed, electron-beam pumped, Krypton Fluoride (KrF) laser that will develop the technologies that can meet the Inertial Fusion Energy (IFE) requirements for durability, efficiency, and cost. Electra will have a 30 cm x 30 cm optical aperture, an output of 400–900 Joules, and run at 5 Hz. The main amplifier will be pumped with two 30 cm x 100 cm e-beams, each with V = 500 kV, I = 110 kA, and t = 100 nsec (flat top). The components that need to be developed are: a durable and efficient pulsed power system; a durable electron beam emitter; a long life, transparent pressure foil structure (hibachi); a laser gas recirculator; and long life optical windows. The technologies developed on Electra will be directly scalable to a full size fusion power plant beam line. We have built a first generation pulsed power system that can produce the necessary pulsed power parameters and repetition rate. This system has operated at 5 Hz for 90,000 shots (e.g. five hours), which is more than ample to develop the laser components. This paper gives an overview of the Electra program, and then concentrate on the results of our research on electron beam generation, transport, and deposition. This includes evaluation of various cathode and hibachi structures, as well as KrF laser modeling.

ample for a fusion system. Simulations of the pellet burn in 2-D and 3-D are also being conducted using commercial and homegrown multiprocessor computers. These simulations will establish the target and laser criteria for current pellet designs and help develop more advanced designs. The simulations and their underlying codes are benchmarked with experiments on the Nike KrF laser at NRL. Nike has demonstrated that a large (3-5 kJ) KrF laser can be built and can produce highly uniform target illumination [3]. The Nike laser generates a beam with the proper pulse shape required for fusion energy, and ablatively accelerates planar targets with nearly the same composition (low density foam wicked with cryogenically cooled liquid D₂) and close to the same areal mass that are required for a high gain system. Moreover, the targets are composed of similar materials as in a high gain target. In addition to these laser-target issues, the Sombrero Power Plant study showed a KrF based system could lead to an economically attractive power plant [4]. The purpose of the Electra program described here is develop the technologies that can meet the fusion energy requirements for rep-rate, efficiency, durability, and cost.

I. INTRODUCTION

Direct drive with krypton fluoride (KrF) lasers is an attractive approach to fusion energy: KrF lasers have outstanding beam spatial uniformity, which reduces the seed for hydrodynamic instabilities; they have an inherent short wavelength (248 nm) that increases the rocket efficiency and raises the threshold for deleterious laser-plasma instabilities; and they have the capability for “zooming” the spot size to follow an imploding pellet and thereby increase efficiency. Numerical 1-D simulations have shown that a target driven by a KrF laser can have a gain above 125 [1,2], which is

II. THE ELECTRA LASER PROGRAM

Electra will be a 700 J, 30 cm aperture, 5 Hz rep-rate facility. It will be 1-2% of the energy of a power plant size laser beam line, but because of the modular nature of the laser, that is large enough for the technologies to be directly scalable to a full size system. The requirements for a fusion power plant laser are based on both power plant studies and on our high gain target designs. A summary of the requirements is shown in Table I, below.

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Table 1 Fusion Energy Requirements for a KrF IFE laser

Parameter	Qty
System efficiency	6-7%
Rep-Rate	5 Hz
Durability (shots) ^[a]	3×10^8
Lifetime (shots)	10^{10}
Cost of entire laser ^[b]	\$250/J(laser)
Cost of pulsed power	\$5-10.00/J(e-beam)
Laser Beam uniformity	< 0.2%
Optical Bandwidth	2-3 THz
Laser Beam Power balance	<2%
Laser Energy-total	1.6-2.4 MJ
Laser Energy (per beam line)	50-150 kJ

[a] Shots between major maintenance (~ 2.0 years)

[b] 2001 dollars. Sombrero study (1992) gave \$180/Joule

The main amplifier of Electra will be pumped with two 30 cm x 100 cm electron beams, each with $V = 500$ kV, $I = 110$ kA, and pulse duration $\tau = 100$ nsec. Electra will use the same type of architecture that would be used in a power plant laser, e.g. double pass laser amplification with double-sided electron beam pumping of the laser gas. This is the same arrangement now being used in the Nike 60 cm amplifier. The main laser components that need to be developed are: a durable, efficient, and cost effective pulsed power system; a durable electron beam emitter; a long life, transparent pressure foil structure (that isolates the laser cell from the electron beam diode the so-called “hibachi”); a recirculator to cool and quiet the laser gas between shots; and long life optical windows. These are shown schematically in Figure 1.

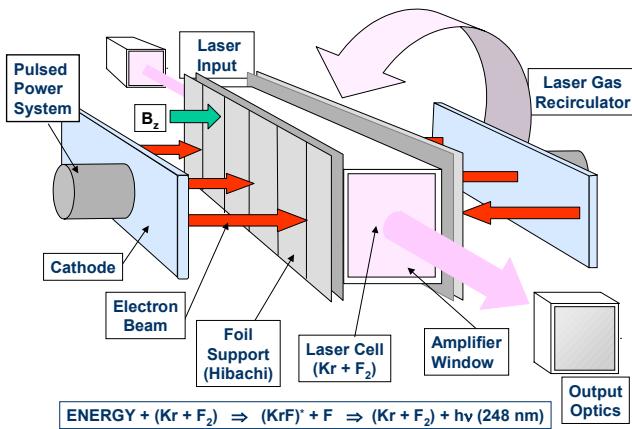


Figure 1. The principal components of an electron beam pumped KrF laser

Technologies that can meet the fusion requirements have been identified [5]. Electra will be built by integrating each component as it is developed to build a single facility.

It will take several years to develop an advanced pulsed power system that can meet all the IFE requirements for durability, efficiency, and cost. Fundamental research and development must be carried out to realize the technology needed to build an appropriate system. However, we do not want to wait until that system is operational before we can start developing the other laser components. Therefore we have developed and built a First Generation Pulsed Power System that is a modest extrapolation of existing technology [6]. While the technology used in this system will not meet the efficiency or durability requirements, it does have the required output and repetition rate. This system uses a capacitor/step-up transformer prime power system that pulse charges a pair of coaxial, water dielectric, pulse forming lines. The energy in the lines is then switched into the electron beam diode load using laser-triggered spark gaps. The First Generation System can run at 5 Hz for 10^5 shots between refurbishment. (Refurbishment is a simple manner of replacing two pairs of electrodes.) This five hour run is unprecedented for a pulsed power system of this size (25 kW @ 500 keV) and is more than ample to develop the required laser components. We have coupled this pulsed power system to the laser development facility, including the magnets, laser cell, both diode boxes and the gas recirculator. A photo of the Electra facility (without the gas recirculator) is shown in Figure 2. Note that there are two identical systems on either side of the laser cell.



Figure 2. The Electra Laser Facility

Regarding the final pulsed power system, we have performed studies of three approaches that have the potential to meet the IFE requirements for durability, efficiency and cost. The first is based on magnetic switches using saturable inductors. This is a low risk concept with respect to existing technology, but the system would be marginal in meeting the cost and efficiency requirements, primarily because the system has to have three stages of magnetic compression. Accordingly, we have evaluated two more systems that have greater promise, but require more research and development. Both are based on laser gated solid state switches. In this approach a small diode laser is used to flood the junction and

volume of a semiconductor switch. This causes the entire switch to turn on very rapidly and allows it to pass a rapidly rising current. In one manifestation the switch operates at 40 kV and is used in an ultra fast Marx arrangement. In another, albeit more difficult approach, the switch operates at up to 1 MV and is used to switch out a water dielectric pulse forming line or Blumlein line. This is a direct replacement for the relatively short-lived high voltage spark gap gas switches such as those used in the present system. Our systems modeling suggests this approach can lead to overall efficiencies of up to 87%. Currently we are performing the advanced component research that is needed to develop both types of laser triggered switches. We are also performing end of life component testing on capacitors and solid state switches to ensure that these components can have the needed durability, and we are performing studies of liquid breakdown in large area, repetitively pulsed systems [7].

One of the key challenges for a long-lived KrF laser system is the development of a cathode and hibachi (foil support structure) that allows the electron beam to efficiently and reliably be injected into the gas. We are evaluating a number of cathode options that can meet the requirements for rise time (< 40 nsec), uniformity ($< 10\%$), impedance collapse (< 1 cm/ μ sec), and durability ($> 3 \times 10^8$ shots.) Ultra fine double velvet cloth meets the first three requirements, but is not expected to have the required durability. To date we have evaluated seventeen different cathodes. The most promising are cathodes based on flocked carbon fiber and on a metal-dielectric structure. Details of our cathode studies can be found elsewhere in these conference proceedings [8]

It is obvious that to meet the efficiency requirements, we need to “patterned the beam” so that it will miss the ribs of the hibachi structure. Our baseline design is to make the hibachi supports out of thin wall tubing that contains flowing water for coolant. A depiction of this is shown in Figure 3.

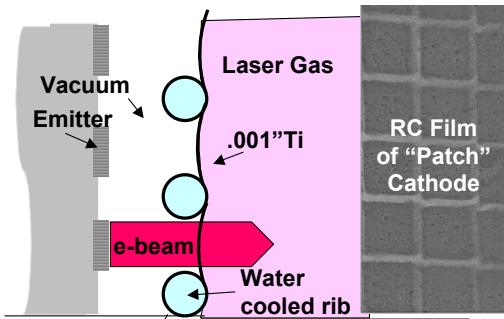


Figure 3: Water Cooled Rib Hibachi Concept

Our preliminary CFD (Computational Fluid Dynamic) analysis shows that this type of arrangement can remove enough of the heat from the foil to keep the system at a reasonable temperature, given the measured foil energy deposition. However more work needs to be done in this area. We have also demonstrated that we can produce an

electron beam in a pattern that is consistent with this concept. We have made the beam in both 1 cm wide by 30 cm high strips and 3 cm x 3 cm patches. The latter is shown in the right hand side of Figure 3, which shows a radiachromic (RC) film image of the electron beam at the anode. This segmenting may also be needed to quench the “transit time instability” discussed below. Getting the beam to pass between the gaps in the ribs is also a challenge, as the applied axial magnetic field used to guide the beam into the laser gas and prevent it from pinching also causes the beam to rotate. This can clearly be seen in the RC film image, and must be taken into account in designing the cathode/hibachi. The most obvious solution is to counter rotate the cathode a fixed amount. In addition to this rotation issue, we also need to establish if this array of close coupled tubes can provide an “electrically flat anode” for the electron beam propagation. Our preliminary experiments using RC film on the backside of the hibachi foil show that there is some loss of electrons when we run without an anode foil compared to when we have an anode foil. However the RC film is a time integrated measurement, and it is believed this loss is due to low energy electrons at the rise and fall of the beam. This will be established with small segmented Faraday cups [9]. Interestingly, we found there was no change in the beam behavior when we made the ribs of ferrous materials. This opens up a much wider range of options for the hibachi, as the ribs are under significant mechanical stress, and ferritic materials are significantly stronger than non-magnetic materials.

We are performing basic and applied research to understand the physics of the electron beam pumped KrF lasers. This includes the development and testing of three codes: an electron beam propagation code to model the electron beam flow through the hibachi structure into the laser cell, an advanced kinetics code to model the e-beam pumped KrF laser media, and a laser beam propagation code to model the laser transport. The ultimate goal of this task is to develop a predictive capability for large electron beam pumped amplifiers, and to possibly increase the intrinsic efficiency of a KrF system to above the $\sim 12\%$ that is presently observed [10]. (Intrinsic efficiency is defined as the laser energy out divided by electron beam energy into the gas.) All of these codes will be tested with experiments on both Electra and the Nike 60cm amplifier. The latter will allow verification close to the scale of a power plant size system. At the present the three codes are being developed separately. They will be combined into a single monolithic code when they are more mature.

Our beam propagation code models the transport of the electron beam in the diode, through the hibachi structure and into the laser gas. This is a Particle in Cell (PIC) Code that includes scattering in the hibachi

foil, back scattering from the laser gas into the diode, and re-injection of the electrons. We have used this model to predict that the water-cooled tube hibachi design described above will allow up to 79% energy of the electron beam energy to be deposited into the laser gas. This is on Electra with an electron beam voltage of 500 keV. In a full scale system operating at 750 keV the expected deposition is 85%. This is more than ample to meet the transport efficiency requirements.

This PIC code has established, along with experiments on Nike, that large area electron beams are subject to a transit time instability [11] which modulates the electron beam at a frequency of 2.5 GHz. The instability imparts an axial momentum spread to the beam electrons which results in a large fraction of the beam being either lost in the foil or completely traversing the cell. The instability also imparts a transverse velocity to the beam which results in a significant fraction of the beam lost to the hibachi ribs. In addition, the electrons can lose 10-20% of their energy to the electromagnetic field, which, in turn, feeds the instability. Obviously this instability is a loss mechanism that must be eliminated. Fortunately, our theory and particle simulations show that the instability can be mitigated, and possibly even eliminated, by slotting the cathode and loading the slots with resistive elements. This effectively turns the cathode-anode into a slow wave structure that damps the RF oscillations. Simulations of the resistively loaded slots showed no sign of any instability. This result was also obtained when the applied voltage was modulated 10% by either white noise or by a 2.5 GHz perturbation. This slotted cathode is consistent with the hibachi designs quoted above, where the electron beam is segmented to miss the hibachi support structure ribs.

In the arena of the KrF kinetics, we are developing a computer code to model the temporal and spatial behavior of e-beam pumped KrF laser amplifiers. The physics is divided into several components: (1) kinetics of the KrF plasma medium, (2) amplification of the seed laser beam, and (3) incoherent propagation of the Amplified Spontaneous Emission (ASE). The plasma is divided into 20 or more zones along the axial lasing direction, with uniform e-beam energy deposition throughout the plasma. This can readily be generalized to full 3-D resolution in the future. The kinetics model follows 23 species, including electrons, for a Kr/Ar/F₂ mixture with 116 reactions. The transport and amplification of the input laser beam is solved using the method of characteristics. This is a stable and accurate technique for handling the exponential gain, and it treats double pass operation with a minimum of additional complication. To date this code can predict the observed output of the Nike 60cm amplifier, as well as with other KrF systems operating in very different regimes. This is the first time a KrF kinetics codes has been able to model a wide range of KrF systems, and gives us confidence that we can develop the required predictive capability.

The gas in the laser cell must be cool and quiescent on each shot to ensure that the amplified laser beam is very uniform. Of particular importance is the elimination of short scale-length, ordered temperature variations perpendicular to the aperture. The EMRLD laser successfully addressed this problem (EMRLD was an electron beam pumped XeF laser developed by AVCO Textron for the Air Force). The gas in the laser cell was circulated through a flow loop that contained a series of mixing plates, diffusers, and heat exchangers. This enabled the EMRLD laser to faithfully amplify a 1.3 x diffraction limited (XDL) laser beam [12]. This is far better than the ~ 5 XDL that is required for Electra. The shot rate was 100 Hz, and the (supply-limited) duration was 10 seconds. As the largest aperture one would consider for a large (50-150 kJ) laser is about 200 cm, these results suggests this technology could readily scale to 5 Hz. A preliminary design shows that a system can be made that meets our power and smoothing requirements [13]. Based on this design, we have produced a first generation recirculator for Electra that will test the baseline flow, the acoustic suppression and the heat removal. The system has been delivered and is undergoing final modifications before installation on Electra.

There are several other components to the Electra Program. Among these is the development of an advanced front end for Electra. This is the initial, low energy stage of the laser system. It will be used to produce the beam temporal and spatial characteristics that is required by the high gain target design; i.e. the ability to precisely control the laser temporal pulse shape, the ability to decrease the laser spot size as the target is compressed (called "zooming"), and the ability to produce flat top spatially uniform profiles on a scale of 4-6 mm diameter. The front end implements the Induced Spatial Incoherence (ISI) beam smoothing that allows KrF lasers to achieve highly uniform and controlled illumination of targets at high intensity. This capability for uniform target illumination is the one of the compelling reasons to develop high-energy high-repetition rate KrF laser technology. Another advantage of a KrF system is that the pulse shaping and zooming tasks can be carried at low energy in a single front end which then feeds all the laser beam lines. Most likely the front end will be some type of electron beam system, as discharge pumped lasers alone cannot produce the needed longer timescale pulses or pump larger apertures.

We also are developing optical coatings for the Electra Amplifier. These need to survive the rather harsh laser cell environment of UV, fluorine, HF, electrons and x-rays. We are using an Ion Beam Assisted Deposition (IBAD) system deposit various coatings of hafnia, magnesium fluoride, or alumina, onto a suitable substrate (usually fused silica). These

are being tested in a controlled environment test cell that mimics the laser cell environment. The coated samples are checked for transmission, uniformity and index of refraction (i.e. n, and k) using a Photospectrometer, an HeNe Laser Probe, and a fiber optic spectrometer. We are also characterizing the surfaces using electron, optical, or atomic force microscopy. The coatings that are found to be resistant to chemical corrosion and have a high enough transmission will be tested for durability to high power laser light. The ultimate goal is a damage threshold of 5 Joules/cm².

III. THE NEXT STEP

Although we discuss only the KrF laser program in this paper, it is part of a larger, broad based integrated program that looks at all the issues for Laser Fusion Energy, including the driver, target gain, chamber, target fabrication, target injection, final optics, materials, and ultimately, the cost of energy. If this entire program is successful in meeting its goals, the next step would be to build an Integrated Research Experiment (IRE). We envision the IRE to be a system that integrates and addresses the key enabling technologies for a KrF laser fusion power plant. The IRE will consist of a laser beam line, steering mirrors, a target injector, and a chamber and will be an integrated repetitive demonstration that a laser beam can be steered to illuminate a target injected into a reactor chamber environment, with the repetition rate, uniformity and precision required for inertial fusion energy. The laser in the IRE will provide the energy, pulse shape control, wall plug efficiency, and target illumination uniformity required for a single beam line of laser fusion power plant. The laser energy and average power on target would be sufficient that this facility could be used for other purposes, such as to examine chamber clearing issues and investigate the response of candidate wall materials to x-ray pulses.

IV. REFERENCES

- [1] S.E. BODNER et al, "High Gain Direct Drive Target Design for Laser Fusion," *Phys of Plasmas* **7**, 2298, (2000). S.E. BODNER et al, "New High Gain target Design for a Laser Fusion Power Plant", Proc IAEA Technical Meeting on Physics and Technology of Inertial Fusion Energy and Chambers June 7, 2000, Madrid Spain.
- [2] D. COLOMBANT, et al., "Effect of Radiation on Direct Drive Laser Fusion Targets," *Phys. Plasmas* **7**, 2046 (2000).
- [3] S.P. OBENSCHAIN, et al., "The Nike KrF Laser Facility: Performance and Initial Target Experiments," *Phys of Plasmas*, **3**, 2098 (1996).
- [4] I.V. SVIATOSLAVSKY, et al., "A KrF Laser Driven Inertial Fusion Reactor Sombrero," *Fusion Technology*, **21**, 1470, (1992).
- [5] J.D. SETHIAN, et al., "KrF Lasers For Inertial Fusion Energy," Proc 17th IEEE Symp on Fusion Engineering, IEEE 0-7803-4226-7/98, p 593.
- [6] J.D. SETHIAN, et al., "Pulsed Power For A Rep-Rate, Electron Beam Pumped, KrF Laser", *IEEE Trans Plasma Sci*, **28**, 1333 (2000).
- [7] I.D. SMITH, D. WEIDENHEIMER, L. SCHLITT, D. MORTON and J. SETHIAN, "Approaches for Breakdown Tests to Better Estimate Operating Levels for Liquid Dielectrics in KrF Laser Power Plants" Digest of Technical Papers, Thirteenth International Pulsed Power Conference, Las Vegas, NV 2001.
- [8] M. MYERS, F. HEGELER, M. FRIEDMAN, and J. SETHIAN, "Development of a Durable, Large Area Cathode for Repetitive, Uniform Electron Beam Generation", Digest of Technical Papers, Thirteenth International Pulsed Power Conference, Las Vegas, NV 2001.
- [9] F. HEGLER, M. FRIEDMAN, M. MYERS, S. SWANEKAMP and J. SETHIAN, "Edge Effect Studies of a Large Area Cathode for the Electra KrF Laser", Thirteenth International Pulsed Power Conf, Las Vegas, NV 2001.
- [10] A. MANDL et al., " KrF Laser Studies at High Krypton Density" *Fus Tech* **11**, 542 (1987).
- [11] M. FRIEDMAN, S. SWANEKAMP, S. OBENSCHAIN, Y. CHAN, L. LUDEKING and D. SMITHE, "Stability of Large Area Electron Beam Diodes", *Appl. Phys Lett* **77**, 1053 (2000).
- [12] P.D. TANNEN et al., "Excimer Laser Technical Support, Final Report", WJSA-FR-A-90-01, January 1990.
- [13] P. LEWIS, "Conceptual Design of a Recirculator for the Electra Laser", Textron Defense Systems, Everett MA, internal report, September, 1999.